US007714309B2

(12) **United States Patent**　　(10) **Patent No.:** **US 7,714,309 B2**

Mackie et al.　　(45) **Date of Patent:** **May 11, 2010**

(54) **PHANTOM FOR ION RANGE DETECTION**

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(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 237 days.

(21) Appl. No.: **12/038,697**

(22) Filed: **Feb. 27, 2008**

(51) **Int. Cl.**
G01N 23/225　　(2006.01)
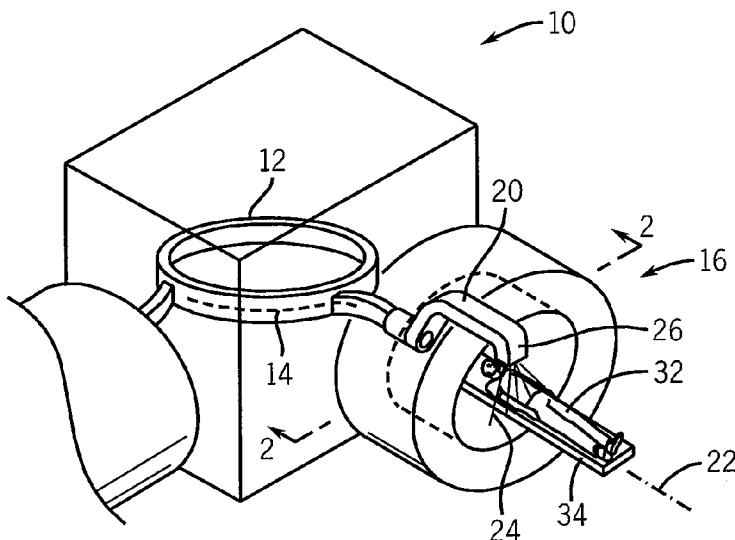*H01J 37/147*　　(2006.01)
H01J 37/30　　(2006.01)
(52) **U.S. Cl.** **250/492.3**; 250/370.1; 250/309;
250/505.1; 250/390.02; 250/390.04; 382/131;
382/132; 378/21; 378/62
(58) **Field of Classification Search** 250/306,
250/307, 309, 370.09, 370.1, 390.02, 390.03,
250/390.04, 390.12, 391, 472.1, 473.1, 492.21,
250/492.3; 378/21, 62, 65, 74, 76, 145–151,
378/901; 382/128, 131, 132
See application file for complete search history.

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(57) **ABSTRACT**

A phantom for heavy ion radiation therapy provides charac-
terization of an ion beam that may enter but not exit from the
phantom. The phantom may include multiple materials and
multiple spatially dispersed ion detectors to obtain signals
that may be fit to known beam curves to accurately charac-
terize the location and other parameters of Bragg peak of a
given ion beam within a patient.

15 Claims, 3 Drawing Sheets

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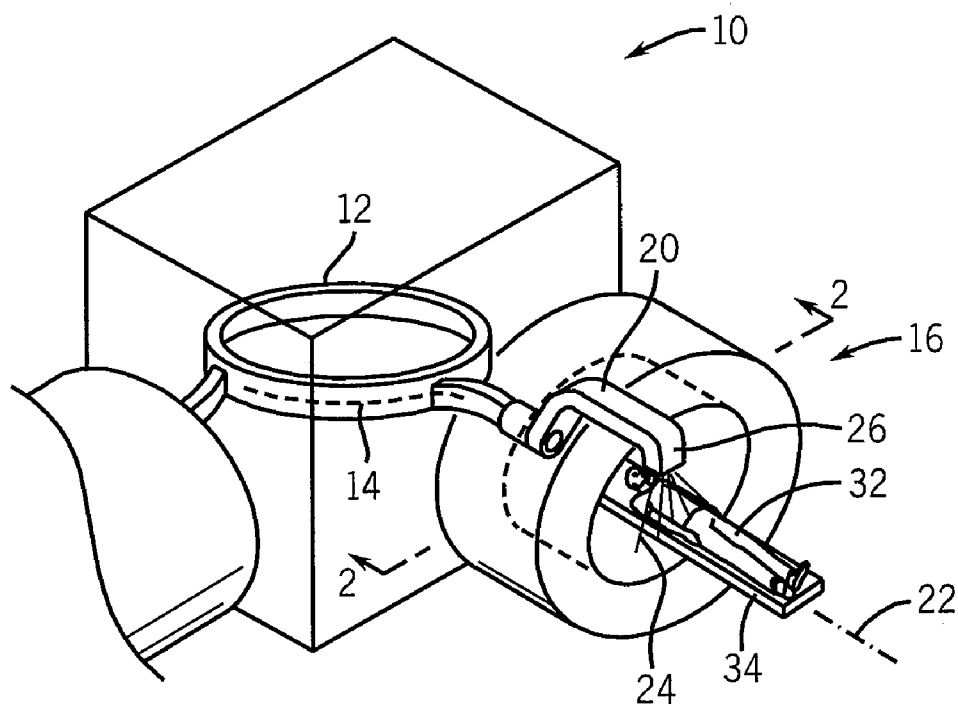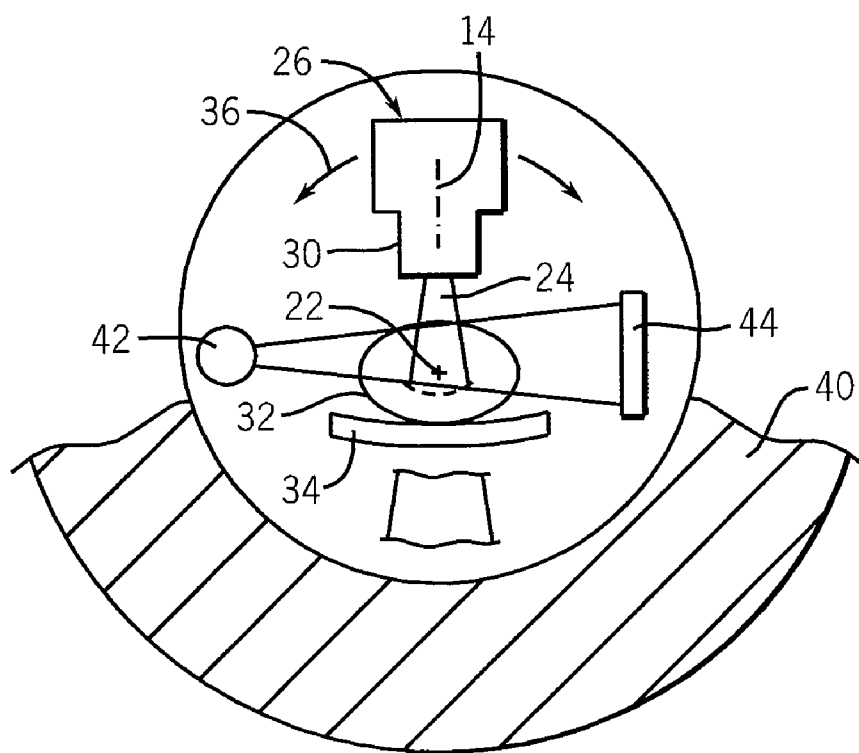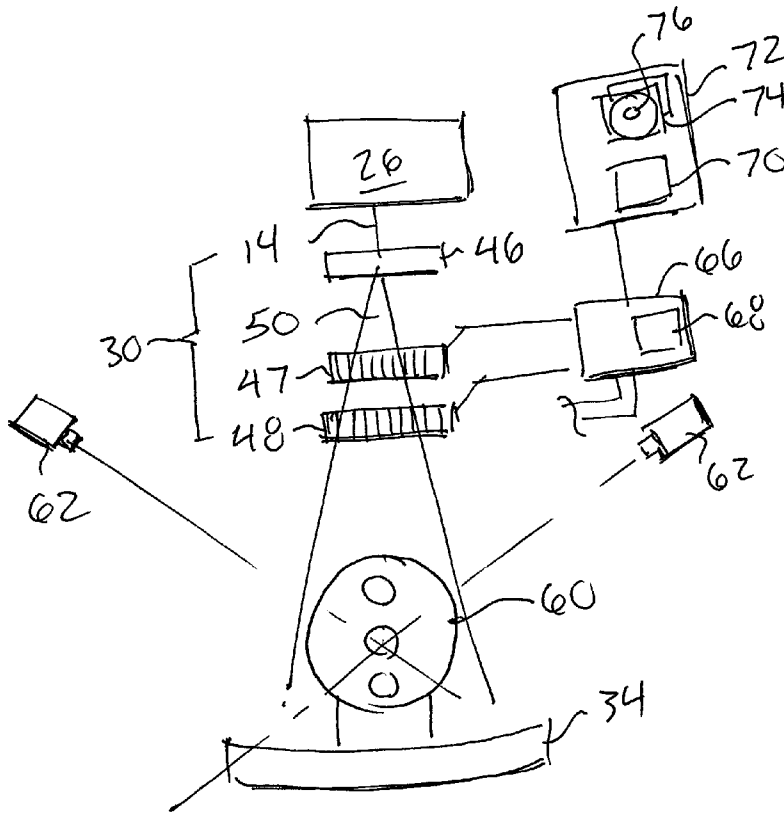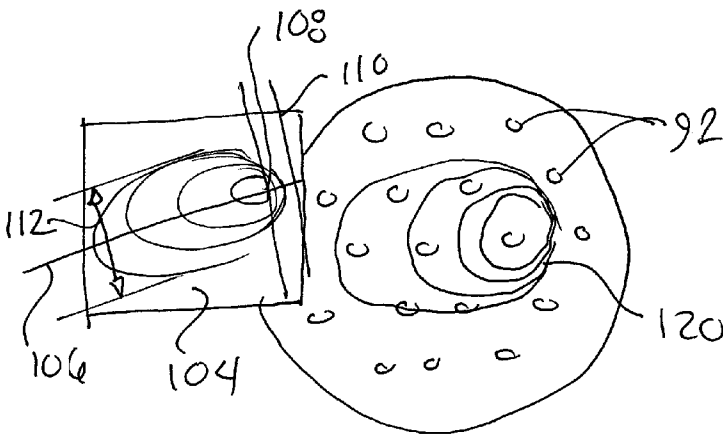
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FIG. 1

FIG. 2

Fig. 3

Fig. 8

Fig 7

Fig. 4

Fig. 6

Fig. 5

Fig. 9

| PLANNING CT | 111 |

| CALIBRATION CT | 113 |

| BRAGG PEAK MEASURE | 114 |

| ADJUST BEAM MODULATION SYSTEM | 116 |

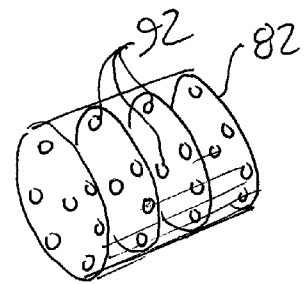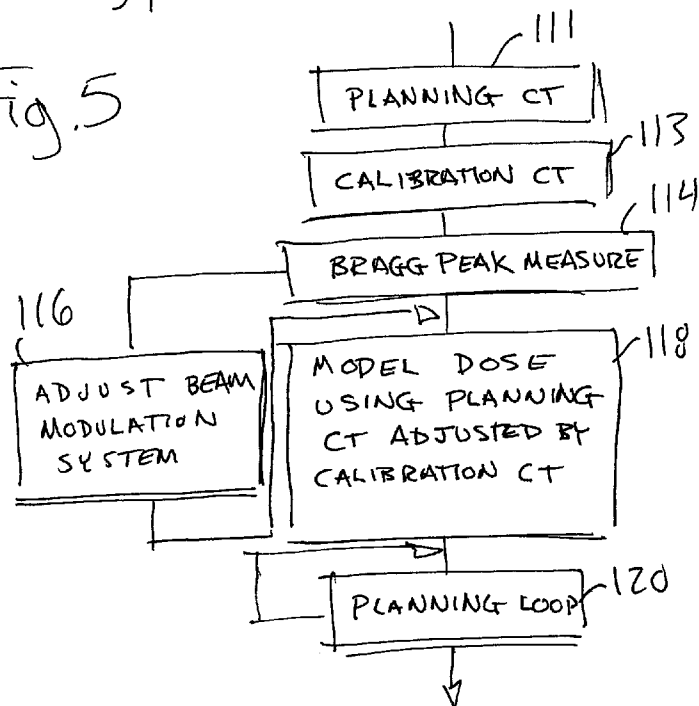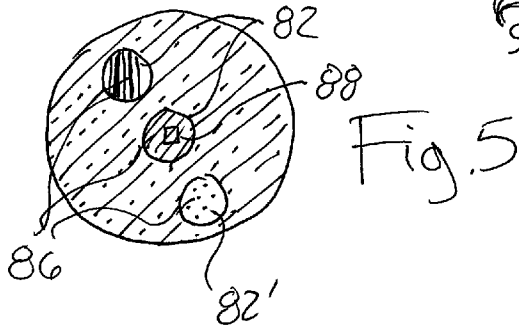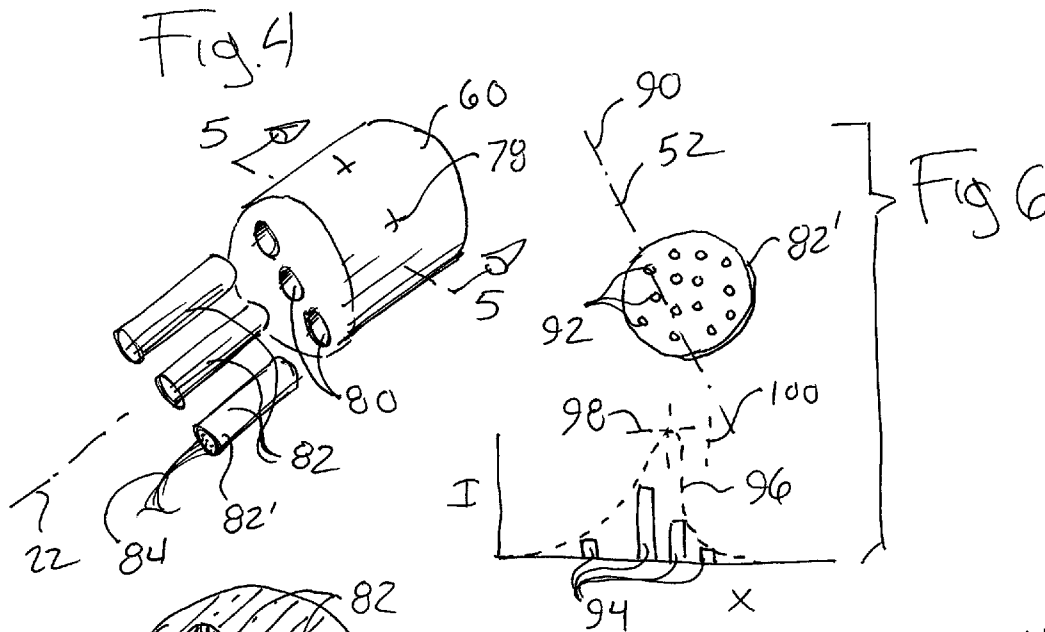| MODEL DOSE USING PLANNING CT ADJUSTED BY CALIBRATION CT | 118 |

| PLANNING LOOP | 120 |

PHANTOM FOR ION RANGE DETECTION

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application 60/891,859, filed Feb. 27, 2007, the disclosure of which is incorporated herein by reference.

This invention was made with United States government support awarded by the following agency:

NIH CA088960

The United States government has certain fights in this invention.

BACKGROUND OF THE INVENTION

The present invention relates to radiotherapy systems using ions for the treatment of cancer and the like and, in particular, to a phantom for such systems.

External beam radiation therapy may treat a tumor within the patient by directing high-energy radiation in one or more beams toward the tumor. Recent advance external beam radiation systems, for example, as manufactured by Tomotherapy, Inc., treat the tumor with multiple x-ray fan beams directed at the patient over an angular range of 360°. Each of the beams is comprised of individually modulated rays whose intensities can be controlled so that the combined affect of the rays over the range of angles provides an arbitrarily complex treatment area with minimized skin dose.

The benefit of the improved accuracy possible with such systems is ensured by careful characterization and monitoring of the x-ray beam geometry and intensity, for example, through portal imaging devices and entrance dose monitors.

X-rays expose tissue not only within the tumor but also along the path of each ray into and out of the patient. While judicious selection of the angles and intensities of the rays of x-ray radiation can limit radiation dose outside of the tumor, a desire to more closely conform the radiation dose to the tumor has raised interest in substituting ions such as protons for x-ray radiation. Unlike x-rays, the dose deposited by a proton beam is not uniform in homogenous tissue, but rises substantially, at the "Bragg peak" just before the proton stops within the tissue. Further, because the proton can be controlled to stop within the tissue, exit does from the proton beam can be substantially eliminated. These two features allow improved placement of dose within the tumor.

Unfortunately, unlike x-rays, ions are not easily characterized by entrance dose monitors and portal imaging device. In part, this is because such devices are sensitive largely to flux (photons per unit time) as opposed to radiation energy, and it is this latter characteristic which determines the important quality of proton range. Portal imaging systems, which rely on radiation exiting the patient, are of limited value in a proton imaging system in which the protons stop within the patient.

SUMMARY OF THE INVENTION

The present invention provides a phantom that may characterize the energy and hence the range of protons. The phantom uses a one or more tissue-mimicking material and an array of intensity detecting elements whose pattern of inten-

sities may locate the Bragg peak. The location of the Bragg peak, in turn, reveals the proton energies. The phantom may be used to calibrate a proton or heavy ion therapy machine and/or may be used to better characterize a CT image used for treatment planning, by equating CT numbers to materials that have been characterized with respect to their interaction with protons.

Specifically then, the present invention provides a phantom including a tissue-mimicking support and a set of ion detectors spatially separated within the tissue-mimicking support to detect passage of ions through the tissue-mimicking support. A data processing system receiving signals from the ion detectors deduces a location within the phantom of a Bragg peak of ions passing through the tissue-mimicking support.

Thus it is one aspect of the invention to provide a measurement system suitable for next-generation ion radiation therapy machines to provide accurate characterization of the ion beam energies.

The tissue-mimicking support may include removable portions wherein the ion detectors are held within one removable portion to be repositioned within the tissue-mimicking support. The removable portions may provide materials representing different tissue types so that portions may mimic different tissue types.

It is thus an aspect of at least one embodiment of the invention to provide a phantom that can characterize the effect of different materials and material thicknesses on Bragg peak location. It is another aspect of at least one embodiment of the invention to allow the phantom to be configured to approximate the actual treatment volume.

The tissue-mimicking support may include fiducial markers allowing automated identification of the different materials in a CT image.

It is thus another object of the invention to allow the phantom to be used to calibrate planning CT images.

The ion detectors may be arrayed both along a direction of propagation of the ion beam and across the direction of propagation of the ion beam and the data processing system may fit a template multidimensional Bragg peak to the signals and spatial locations of the ion detectors to identify the Bragg peak.

It is thus an aspect of the present invention to provide for multidimensional characterization of the Bragg peak including range and beam widening. It is another aspect of the invention to allow characterization of the beam center line.

These particular features and advantages may apply to only some embodiments falling within the claims and thus do not define the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view in partial phantom of an example proton therapy system suitable for use with the present invention having a synchrotron proton source providing protons to multiple gantry units;

FIG. 2 is a cross-section along line 2-2 of FIG. 1 showing a proton beam modified by a beam control system before being directed into a patient;

FIG. 3 is a block diagram of the beam control system of FIG. 2;

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FIG. **4** is a perspective view of a phantom positionable in place of the patient of FIG. **2**, the phantom having removable plugs of tissue-mimicking material held by a larger tissue-mimicking support, and further showing one plug as instrumented with ion detectors;

FIG. **5** is a cross-section along line **5-5** of FIG. **4** showing a configuration of the plugs inserted into the phantom and showing a radio opaque fiducial marker on one plug for CT identification;

FIG. **6** is an elevational, cross section of the plug instrumented with ion detectors showing a centerline of an ion beam through detector elements, and a plot of the signals from the elements as fit to a Bragg peak of the ion beam;

FIG. **7** is a perspective view of a three-dimensional array of detector elements;

FIG. **8** is a plot of isodose lines for a standard Bragg peak being part of a set of isodose surfaces that may be fit to the isodose surfaces measured by the detector of FIG. **7** to locate the Bragg peak in the phantom; and

FIG. **9** is a flow chart for use of the phantom of the present invention for calibrating the gantry system and/or for treatment planning.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. **1**, a ion therapy system **10** may include a cyclotron or synchrotron **12** or other proton source providing a pencil beam of protons **14** to a gantry unit **16**.

Referring also to FIG. **2**, the proton beam **14** may be received along an axis **22** into an axial portion of a rotating arm **20** rotating about the axis **22**. The rotating arm **20** includes guiding magnet assemblies of a type known in the art to bend the proton beam **14** radially away from the axis **22** then parallel but spaced from the axis **22** to a treatment head **26**. The treatment head **26** orbits about the axis **22**c with rotation of the rotating arm **20** bending the proton beam **14** back toward the axis **22**.

The treatment head **26** may include a modulation assembly **30** for forming the proton beam **14** into a wider treatment beam (for example a fan or cone beam) and for modulating rays of the beam in energy and intensity to produce a modulated treatment beam **24** as will be described.

Referring still to FIG. **2**, a patient **32** may be positioned on a support table **34** extending along the axis **22** so that a modulated treatment beam **24** may irradiate the patient **32** at a variety of angles **36** about the axis **22**. A cylindrical neutron shield **40** having a bore for receiving the table **34** and the rotating arm **20** may surround the gantry unit **16** to block generated neutrons.

In one embodiment, a second rotating arm (not shown) may rotate with or independently of the rotating arm **20** to support an x-ray source **42** and x-ray detector **44** opposed across the axis **22** to illuminate the patient **32** at a range of angles to provide a CT scan of the patient **32** according techniques well-known in the art.

Referring now to FIG. **3**, the modulation assembly **30** may include a fan beam former **46**, followed by an energy or range modulator **47**, followed in turn by an intensity modulator **48**. The fan beam former **46** may receive the monoenergetic pencil beam of protons **14** having a generally small circular

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cross-section to widen this beam into a treatment beam **50** being for example a larger circle (a cone beam) or a thin rectangle extending perpendicular to axis **22** (a fan beam). The range modulator **47**, receives the treatment beam **50** and changes the energy of the protons in different rays **52** of the treatment beam **50**, for example by selective insertion of different thicknesses of materials as taught in U.S. Pat. No. 5,668,371 entitled: "Method and Apparatus for Proton Therapy" assigned to the same assignee as the present invention, and hereby incorporated by reference.

The treatment beam **50** then is received by the intensity modulator **48** which may, for example, be a set of shutters, one for each ray **52**, controlling the amount of time the protons may pass along that ray **52** thus defining an average intensity of protons in each ray **52** as it also taught by the above referenced patent.

The modulated treatment beam **24** having rays **52** that are both intensity and energy modulated may be directed toward a phantom **60** of the present invention fixed at a known location with respect to the table **34**. This precise location of the phantom may be assisted by means of laser line projectors **62** directing lasers toward an isocenter along axis **22**, the isocenter being **64** defining the center of rotation of the treatment head **26** and matching with fiducial markings on the outside of the phantom **60** as will be described.

The range modulator **47** and intensity modulator **48** may be controlled by a control system **66** including a calibration memory **68** providing a conversion between the desired intensity and actual physical shutter settings of the range modulator **47** and intensity modulator **48**. The control system **66** may receive a treatment plan **70** from a general purpose computer **72** executing a stored program as will the described to generate the treatment plan from one or more CT images **74** having a user-defined dose pattern **76** superimposed thereon. Computer **72** may also provide for a CT reconstruction by controlling and monitoring of x-ray source **42** and detector **44** described above and may provide other control functions generally understood in the arc.

Referring now to FIG. **4** the phantom **60** may for example be generally cylindrical with the axis of the cylinder aligned, when it is placed on the table **34**, with axis **22**. And outer surface of the cylinder may include fiducial markings **78** that may align with the laser scans of laser line projectors **62** to allow precise and known placement of the phantom on the table **34** and thus its location with respect to the treatment head **26**. The phantom in one embodiment may include a set of axial bores **80** of cylindrical dimension that may receive corresponding cylindrical inserts **82**. The main body of the phantom **60** may be, for example, a water mimicking material such as Plexiglas or polyethylene or other hydrocarbon material while the inserts may be of the same material or different materials for example those simulating bone or lungs, these latter materials compounding, for example, calcium and phosphorus compounds mixed in with plastic or micro spheres to provide for air inclusions decreasing the density of the plastic material.

One of the inserts **82** may be a detection insert **82'** providing a series of ion detectors or MOSFET or scintillation detectors embedded in the insert **82'** and communicating

through cabling **84** with a data acquisition system associated with computer **72**, as shown in FIG. **3**, or a freestanding data acquisition system.

Referring now to FIG. **5**, a CT image of the phantom **60** will provide for image areas **86** associated with the main body of the phantom **60** and each of the inserts **82**. Each image area may provide a characteristic CT number or image grayscale value. The inserts **82** may include radio-opaque fiducial markings **88**, for example, allowing them to be automatically recognized in the CT image, for example, as may be fashioned from as lead beads or wire. Improved discernment of the type of material may be provided, for example, through dual energy CT techniques or the like.

Referring now to FIG. **6**, a ray **52** extending along a ray axis **90** may pass through the plug **82'** to be measured by one or more detector elements **92**. Each of these detector elements **92** provides a signal **94** having a strength I and a spatial location x. The spatial location will generally describe up to three dimensions, but as shown is a single dimension along the known axis **90**. These signals **94** may be fit to a Bragg peak template **96** having a characteristic shape that may be scaled in the x and I dimensions to provide a best fit to the signals **94**. Once the Bragg peak template is fit to the signals **94**, Bragg peak maximum **98** and Bragg peak location **100** may then be determined.

Referring now to FIG. **7** the detector elements **92** may be distributed in three dimensions within the plug **82'** to provide not only a Bragg peak location but a three-dimensional characterization of the proton beam distribution.

Referring now to FIG. **8** a two-dimensional implementation of this process for example takes the signals **94** from each of the detectors in multiple dimensions to generate an isodose surface **102** which may be fit to a template standard isodose surface **104** with scaling, translation and rotation which may be used to determine proton beam characteristics including beam axis **106**, beam peak **108**, beam limit **110**, and beam width **112** byte reading from the template as so scaled, translated, and rotated. It will be understood that this process may be readily extended to a complete three-dimensional characterization of the proton beam even though the beam does not exit the phantom **60**.

Referring now to FIG. **9**, the phantom **60** may be used in a procedure with the system of FIG. **1** to provide improved characterization of the ion beam and of the patient for planning purposes. At a first process block **111**, a planning CT images taken of the patient in a manner similar to that done for standard x-ray Tomotherapy. This is followed or preceded by a calibration CT scan indicated by process block **113** of the phantom **60**.

As indicated by process block **114**, the radiation therapy machine **10** is then used to irradiate the phantom **60** to determine the Bragg peak location for the phantom **60** as calibrated at step **113**. This Bragg peak information is used for two purposes. In its initial purpose, as indicated by process block **116**, the Bragg peak measurements are extracted and used as to adjust and calibrate the modulation assembly **30** through, for example, adjustment of calibration factor table **68** described with respect to FIG. **3**. In this way the radiation therapy machine can produces the energies and beam spread expected in its operation.

The Bragg peak information is also used as indicated by process block **118** to improve the radiation planning process. In this use, materials of the planning CT of the patient taken at process block **111** are matched to the known materials on the phantom **60** by matching grayscale values of the calibration CT image taken at process block **113** with the planning CT image taken at process block **111**. An improved model of the patient is thereby produced and used to evaluate different beam intensities and ranges according to a planning loop **120** which in its simplest form uses a Monte Carlo or simple similar technique to perturb intensities and ranges of the beams and to model those iteratively against the model produced. Alternatively as disclosed in the previously cited U.S. Pat. No. 5,668,371 the beam ranges may be placed using distal edge algorithm described in that patent and the intensities alone may be iteratively modeled using the attenuating properties all the materials alone.

It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein, but include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims.

We claim:

1. A ion phantom comprising:
a tissue-mimicking support;
a set of ion detectors spatially separated with in the tissue-mimicking support to detect passage of ions through the tissue-mimicking support; and
a data processing system receiving signals from the ion detectors to deduce a location within the phantom of a Bragg peak of ions passing through the tissue-mimicking support.

2. The ion phantom of claim **1** wherein the tissue-mimicking support includes removable portions and wherein the ion detectors are held within one removable portion to be repositioned within the tissue-mimicking support.

3. The ion phantom of claim **2** wherein the removable portions provide materials representing different tissue types so that portions may mimic different tissue types.

4. The ion phantom of claim **1** wherein the tissue-mimicking support includes different materials mimicking of different tissue types.

5. The ion phantom of claim **4** wherein the tissue-mimicking support further includes fiducial markers allowing automated identification of the different materials in a CT image.

6. The ion phantom of claim **1** wherein the ion detectors are arrayed both along a direction of propagation of the ion beam and across the direction of propagation of the ion beam and wherein the data processing system fits a standard multidimensional Bragg peak to the signals and spatial locations of the ion detectors to identify the Bragg peak.

7. The ion phantom of claim **1** wherein the ion detectors are arrayed both along a direction of propagation of the ion beam and across the direction of propagation of the ion beam and wherein the data processing system receives the signals from the ion detectors to deduce a centerline of the ion beam.

8. A ion therapy apparatus comprising:
a ion beam source;
a modulation system receiving control signal and ions from the beam source to provide a set of spatially separated ion beams modulated in energy and intensity according to the control signal;

a phantom positionable within the ion beams and providing a set of ion detectors within a tissue-mimicking support;

a data processing system receiving signals from the ion detectors to deduce a Bragg peak of at least one ion beam within the phantom; and

a control signal adjuster receiving Bragg peak data from the data processing system to adjust the modulation system.

9. The ion therapy apparatus of claim **8** wherein the tissue-mimicking support includes removable portions and wherein the ion detectors are held within one removable portion to be repositioned within the tissue-mimicking support.

10. The ion therapy apparatus of claim **9** wherein the removable portions provide materials representing different tissue types so that portions may mimic different tissue types.

11. The ion therapy apparatus of claim **8** wherein the tissue-mimicking support includes different materials mimicking of different tissue types.

12. The ion therapy apparatus of claim **8** wherein the ion detectors are arrayed both along a direction of propagation of the ion beam and across the direction of propagation of the ion beam and wherein the data processing system fits a standard multidimensional Bragg peak to the signals and spatial locations of the ion detectors to identify the Bragg peak.

13. The ion therapy apparatus of claim **8** wherein the ion detectors are arrayed both along a direction of propagation of the ion beam and across the direction of propagation of the ion

beam and wherein the data processing system receives the signals from the ion detectors to deduce a centerline of the ion beam.

14. A ion therapy system comprising:

a phantom providing a series of different tissue-mimicking materials;

a computed tomography system for obtaining a CT image of a treatment volume of a patient and of the phantom;

a dose identification tool receiving input from a user to demarcate a desired dose to the treatment volume with respect to the CT image;

a treatment plan calculator receiving the desired dose and the CT image of the phantom end of the patient, the treatment plan calculator operating to:

(i) model tissue characteristics of the treatment volume with respects to an ion beam using materials of the phantom matching within the CT images of the patient and the phantom; and

(ii) determine a treatment plan using the model;

a modulatable ion beam source for irradiating the treatment volume with ions according to the treatment plan.

15. The ion phantom of claim **14** wherein the phantom further includes fiducial markers allowing automated identification of the different tissue-mimicking materials in the CT image of the phantom.

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